11. Laser Ranging Retroreflector

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Concept of the Experiment

During the Apollo 14 mission, a second laser ranging retroreflector (LRRR) was deployed on the lunar surface. The Apollo 11 and 14 retroreflector packages permit ground-based stations to conduct short-pulse laser ranging to these arrays on the lunar surface. An observation program of several years' duration that results in an extended sequence of high-precision Earth-Moon distance measurements will provide data from which a variety of information about the Earth-Moon system can be derived (refs. 11–1 to 11–7).

An obvious immediate use of these data will be to define more precisely the motion of the Moon in its orbit. Another experimental result will be the measurement of the lunar librations—the irregular motions of the Moon about its center. Most of the apparent librations are caused by the ellipticity of the lunar orbit and the inclination of lunar axis of rotation, but residual motions are present because the mass of the Moon is not evenly distributed. The Apollo 11 retroreflector site and the Fra Mauro Apollo 14 site, though both near the equator, are well separated from one another and consequently will yield high-quality information concerning the librations of the Moon in longitude. The ability to separate the librations in longitude from the center of mass motion of the Moon will be of significant value in the analysis of the lunar-range results.

It has not yet been possible to conduct a full calculation of the lunar librations with the accuracy needed for the laser ranging experiment. A third U.S. retroreflector is to be deployed as a part of the Apollo 15 mission in the area near Rima Hadley. The three Apollo arrays, well separated in longitude and latitude, will permit a complete geometrical separation of the lunar librations. Already, the existence of two arrays should make it possible to see a phase shift in the 3-yr physical librations, which Eckhardt has recently pointed out (ref. 11–8) should exist unless the Q of the Moon is very high.

Another major objective of this experiment is to learn more about the Earth. Current theories suggest that the surface of the Earth is subdivided into a number of large plates that move with respect to one another. These movements are believed to explain continental drift. As an example, the Pacific plate is thought to be moving toward Japan at the rate of about 10 cm/yr. After observation stations are established in Hawaii and Japan, the lunar-distance measurements will give the longitudes of these stations with such high accuracy that this expected motion should be observable within 2 or 3 yr.

Data obtained from the lunar-distance measurements will also determine the position of the North Pole with an accuracy of approximately 15 cm,

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which is five or 10 times more accurate than that presently known by current methods. The position of the pole moves around the surface of the Earth in a rather complicated manner. It may travel nearly 70 m along a rather elliptical path during any year. The excitation mechanism for this polar wobble is still much in debate. It cannot be conclusively stated whether the mechanism is atmospheric mass shifts, variations in the coupling of the core and the mantle, or mass shifts in the crust. The last hypothesis has been suggested by a correlation of observed polar shifts with major earthquakes, and hence better measurements may lead to a more complete understanding of earthquake phenomena.

Lunar-distance measurements will also permit more accurate determinations of the Earth rotational rate than has previously been possible. And, finally, the sensitivity afforded by the presence of these retroreflecting arrays on the lunar surface will make it possible to use the Moon again as a testing ground for gravitational theories. Many observers are interested in discovering whether the tensor theory of gravity is sufficient or whether a scalar component is necessary, as has been suggested. A definitive test of the hypotheses may be obtained by monitoring the motion of the Moon. Additionally, the possibility exists of seeing some very small but important effects in the motion of the Moon that are predicted by the general theory of relativity.

Properties of the LRRR

The Apollo 14 LRRR (figs. 11–1 and 11–2) is a wholly passive device containing an array of 100 small, fused-silica corner cubes, each 3.8 cm in diameter. The Apollo 14 LRRR was deployed during the first period of extravehicular activity approximately 30 m west of the central station; thus, the array was placed approximately 200 m west of the lunar module (LM). Leveling and alinement to point the normal-to-the-array face toward the center of the Earth libration pattern was accomplished with no difficulty (fig. 11–3). Each corner cube in the array has the property of reflecting light parallel to the incident direction; that is, a light beam incident on a corner cube is internally reflected in sequence

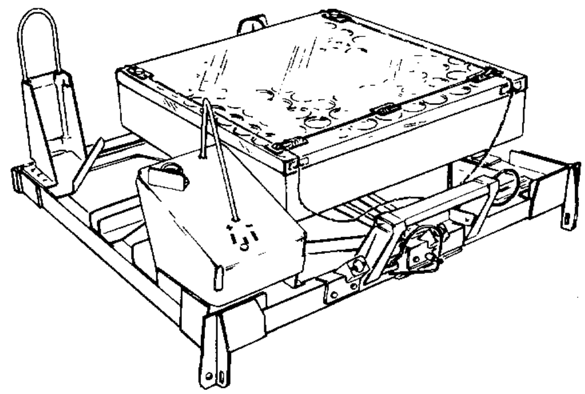

FIGURE 11–1.—The LRRR in a stowed configuration.

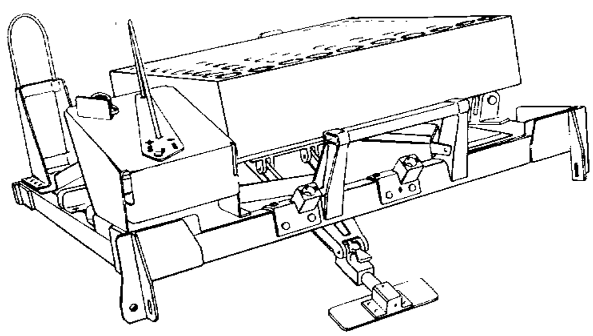

FIGURE 11–2.—The LRRR in a deployed configuration.

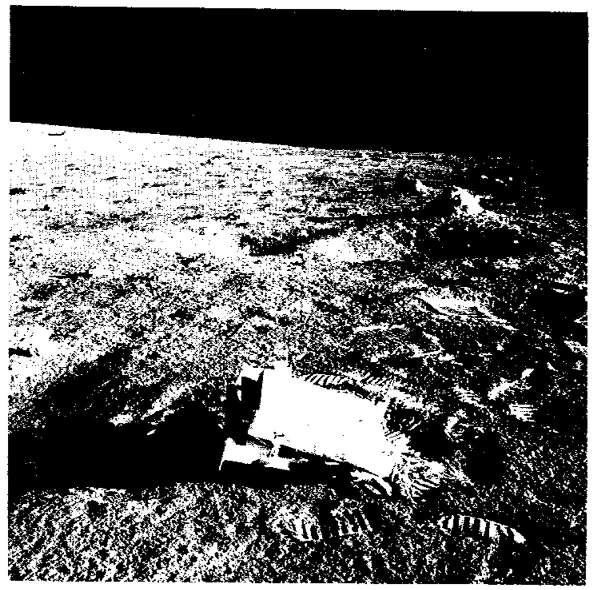

FIGURE 11–3.—Photograph of the deployed Apollo 14 array.

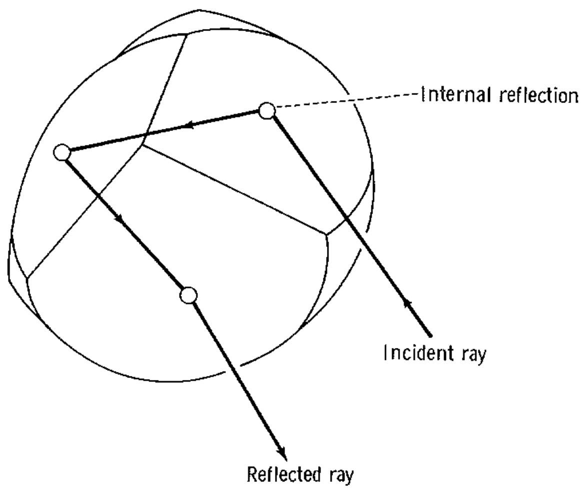

FIGURE 11–4.—Typical laser-ray path in retroreflector.

from the three back faces and then returned along a path parallel to the incident beam (fig. 11–4). This parallelism between the reflected and incident beams insures that the reflected laser pulse will return to the vicinity of origin on the Earth.

The Apollo 14 LRRR is almost identical to the Apollo 11 array placed on the Moon in July 1969 (ref. 11–9). The basic array design is a result of the need to meet and simultaneously satisfy many different and sometimes conflicting requirements. In an ideal environment, the choice would be relatively simple because, for a given geometry and allowable weight (payload), the return signal is maximized by making a single diffraction-limited retroreflector as large as weight restrictions and fabrication techniques will permit. Two aspects of the practical problem, however, vitiate this conclusion: (1) a displacement occurs in the returned laser beam because of the relative velocity between the Moon and the laser transmitter (velocity aberration) and (2) a wide lunar-temperature variation occurs from full Moon to new Moon, as well as the fact that the retroreflector is exposed essentially half the time to an energy input from direct sunlight. The velocity aberration that displaces the center of the returned diffraction pattern between 1.5 and 2 km limits the diameter of the diffraction-limited retroreflector that can be used to approximately 12 cm unless two telescopes spatially separated from one another are used, one for transmitting and the other for receiving. In the situation in which laser light is transmitted and received at the same location, analysis shows that the loss in efficiency that results from using a large number of smaller diameter corners is almost exactly compensated as a result of the increased diffraction spreading of each corner. This has the effect of placing the transmitter-receiver site higher up the side of the returned diffraction pattern. These two effects result in essentially the same optical efficiency for a given payload weight for corners ranging from approximately 3.8 to 12 cm in diameter. With the use of a corner smaller than 3.8 cm, an overall loss in efficiency is experienced because further diffraction spreading is ineffective; at that size, the single transmitting and receiving site is already, for all practical purposes, at the center or peak of the returned diffraction pattern. The observations that dictated the choice of 3.8 cm as the diameter of the corners were as follows: (1) using this smallest still-efficient size made it possible to minimize the thermal gradients that would distort the individual cube-corner diffraction patterns and (2) with this size corner, one could expect to achieve essentially diffraction-limited performance throughout the lunar day as well as during lunar night. The temperature gradients in the individual corner cubes are further minimized by recessing each reflector by half its diameter in a circular socket (fig. 11–5). Furthermore, each reflector is tab mounted between two Teflon rings to afford all possible thermal insulation. The mechanical mounting structure serves

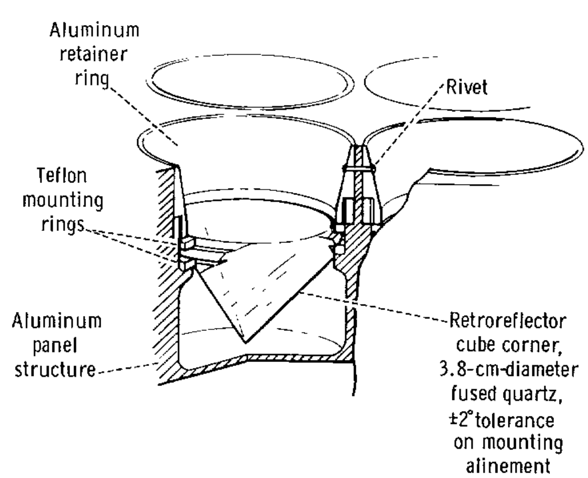

FIGURE 11–5.—Retroreflector mounting.

also to provide passive thermal control by means of surface properties. A transparent polyester cover assembly protected the array from dust during storage, transportation, handling, and flight. The Apollo 14 crew removed this cover at the time of deployment.

The Apollo 14 LRRR differs from the earlier Apollo 11 design in only two main aspects:

(1) The array cavity design was changed to increase the half-angle taper from 1.5° to 6° to decrease the obscuration and thereby increase the array optical efficiency approximately 20 to 30 percent for off-axis Earth positions.

(2) The supporting pallet is lighter and somewhat simpler in design.

Successful range measurements to the Apollo 14 array were first made from the McDonald Observatory of the University of Texas on February 5, 1971, the day on which the LRRR was deployed by the crew. Ranging subsequent to LM liftoff indicated that no serious degradation of the retroreflectors has occurred as a result of the ascent-stage engine burn. Signal strengths compare favorably with the levels obtained over the past year from the Apollo 11 array.

Ground-Station Operation

At present, range measurement to the two retroreflector packages at nearly all phases of the Moon are being conducted at the McDonald Observatory with NASA support. Return signals from the Apollo 11 array have also been obtained by the Pic du Midi Observatory in France and the Air Force Cambridge Research Laboratories Lunar Laser Observatory near Tucson, Ariz. Recent reports suggest that the ranging group in Japan has also had some initial success. It is hoped that several other lunar ranging stations will be in operation within the next year or two, including stations in Hawaii, Russia, and the Southern Hemisphere.

A line drawing of the laser ranging station at the McDonald Observatory is shown in figure 11–6. A schematic drawing of the telescope matching optics and guider is shown in figure 11–7. The present observation program at the McDonald Observatory consists of three observing periods on most nights when the weather permits,

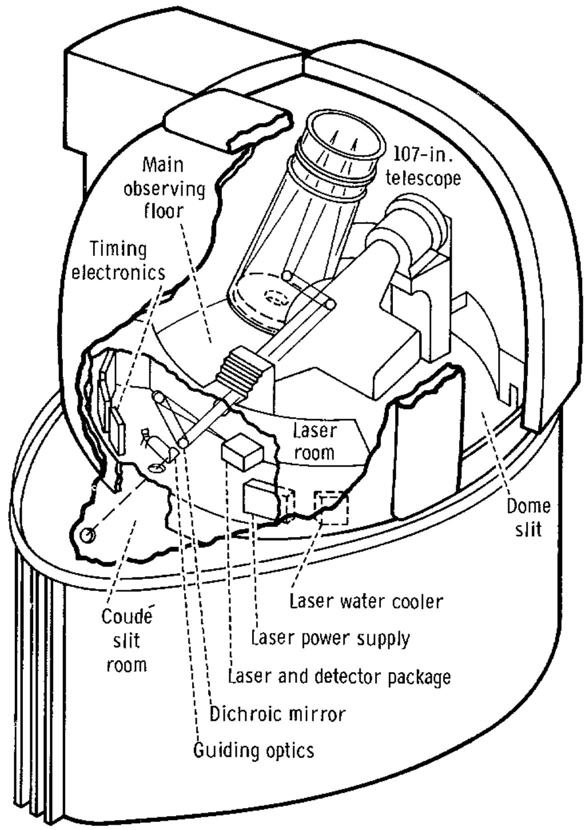

FIGURE 11–6.—Cutaway drawing of McDonald Observatory 107-in. telescope.

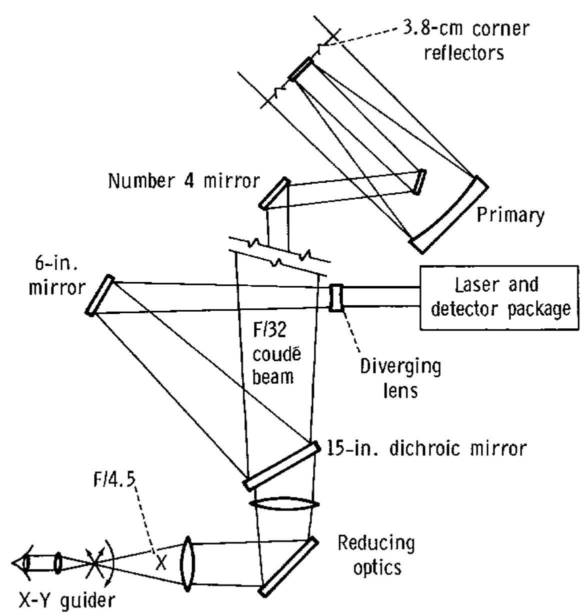

FIGURE 11–7.—Telescope matching optics and guider.

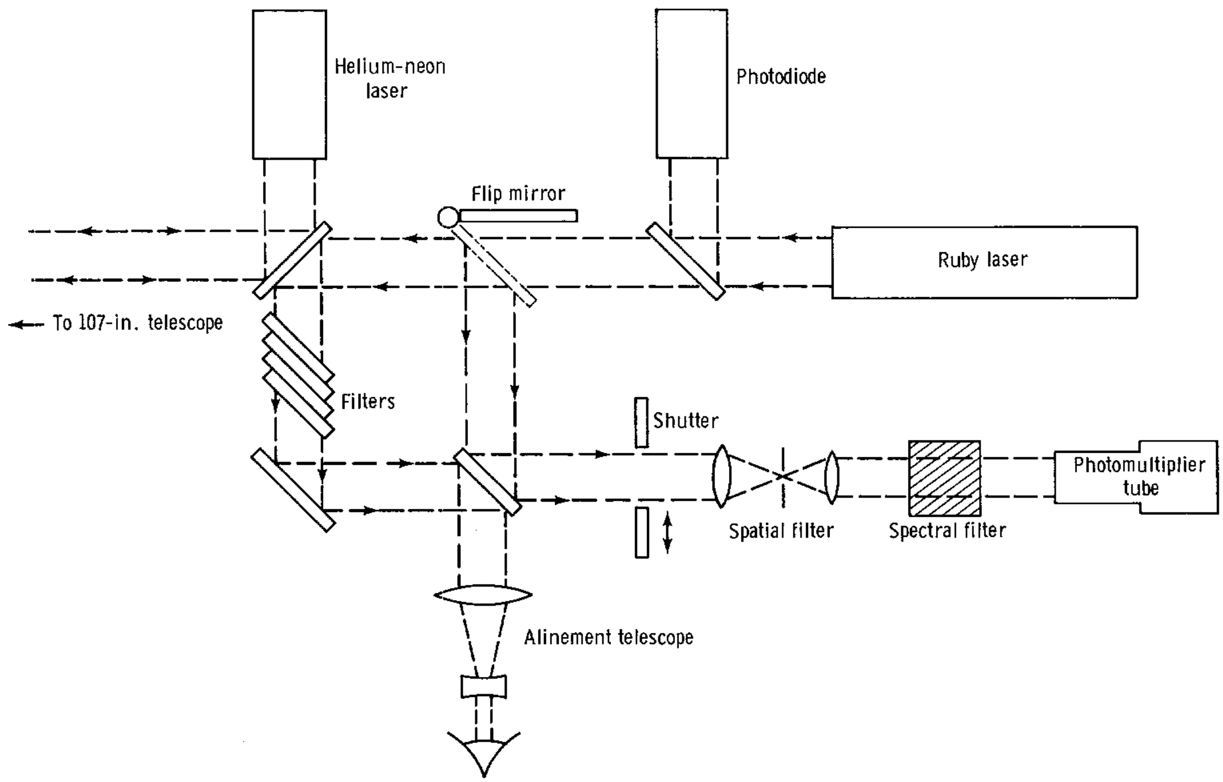

FIGURE 11–8.—Lunar ranging detector package.

except for a period of 5 days around the new Moon. One observing period is near the time of meridian transit for the Moon, and the others are 3 or 4 hr earlier and later. Several runs of approximately 50 shots each are normally fired during each observing period.

During the past year, considerable effort has been successfully exerted in the areas of equipment and calibration procedures.

The ruby laser system being used at present gives 3–J pulses with a repetition rate of one pulse every 3 sec. The total pulse length between the 10-percent intensity points is 4 nsec. The root-mean-square variation in the observed transit time, because of the laser pulse length and the jitter in the photomultiplier receiving the returned signal, is 2 nsec. The present overall accuracy of the measured transit time is ± 1 nsec (equivalent to an error of approximately ± 30 cm in distance measurements). Improvement to less than 1 nsec is expected with further refinements in the calibration procedures. Recent progress in lasers permits the use of pulses with a 0.2-nsec length. This narrow pulse capability should prove extremely valuable in achieving the scientific goals of the experiment. The present detector-package arrangement is shown diagrammatically in figure 11–8.

With data from two or more well-located observing stations, the lunar range can be corrected accurately for the effects of polar motion and fluctuations in the Earth rotational rate. The uncertainty in range, as a result of the atmosphere in general, will be less than 1 cm for zenith angles of up to 70°.

Summary

The placing of the Apollo 11 retroreflector array on the Moon in July 1969, together with successful deployment of the Apollo 14 array, has resulted in a dramatic change in man's ability to measure the Earth-Moon distance. As in many astronomical and geophysical measurements, full scientific results will be obtained only after many years of monitoring variations in the lunar distance. Experience to date gives every indication that both arrays will continue to function toward achieving the scientific ends of the experiment by providing primary benchmarks on the lunar surface for years to come.

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